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EXECUTIVE SUMMARY

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Halon 1301 (CF_3Br), one of the chemicals identified as detrimental to stratospheric ozone, had become the choice for suppressing in-flight fires in nearly all types of aircraft. Production of new halon 1301 was stopped on January 1, 1994, and efforts are underway to identify near-term replacements for critical applications, focussing on available or currently emerging chemicals and technologies. In particular, the three military services and the Federal Aviation Administration (FAA) have pooled resources to provide solutions for two applications: engine nacelles and dry (avionics) bays, while realizing that there are other aircraft areas also in need of protection. This project was managed at Wright Patterson Air Force Base (WPAFB), with oversight provided by a Technology Transition Team of the four sponsors.

The first major objective of the program was to identify the optimal available alternative fluid(s) for use in suppressing fires in aircraft engine nacelles and dry (avionics) bays. In October, 1993, based on extensive laboratory research and real-scale testing at WPAFB, the sponsors decided on a reduced list of candidates for each application; for engine nacelles: C_2HF_5 (HFC-125), C_3HF_7 (HFC-227ea), and CF_3I; for dry bays: C_2HF_5, C_3F_8 (FC-218), and CF_3I. Much of the laboratory-scale research leading to that decision has been described in NIST Special Publication 861, *Evaluation of Alternative In-Flight Fire Suppressants for Full-Scale Testing in Simulated Aircraft Engine Nacelles and Dry Bays*. That report documents the comprehensive experimental program to screen the performance of possible suppressant chemicals as a means to identify the best candidates for subsequent full-scale aircraft fire extinguishment evaluation at Wright Laboratory, and addresses the compatibility of these agents with flight systems, people, and the environment. In particular, apparatus and measurement methods suited to aircraft applications are carefully described, and extensive performance data are provided and analyzed. The reader is referred to that report as a prerequisite and companion to the current document.

The subsequent research described in this report falls into two broad categories:

Part 1: Knowledge to help differentiate among chemicals, leading to selection of the optimal currently available option(s) for in-flight fire suppression

Fire Suppression Efficiency. Most of the laboratory-scale information was reported in SP 861. In new studies in a deflagration/detonation tube, simulating fire suppression in a dry bay, FC-218 provided the best overall performance; HFC-125 was comparable under many conditions. CF_3I had the greatest positive impact at low addition levels, but showed non-monotonic behavior of flame speed and shock pressure at higher levels. In fire suppression efficiency measurements in a turbulent spray burner simulating engine nacelle fires, CF_3I was found to be more efficient than either HFC-125 or HFC-227ea. However, at an elevated temperature of 150 °C, the three chemicals performed equally on a mass basis.

Stability During Storage. There should be no problems with designing long-term storage capability for any of the four agents. The agents were tested for chemical stability in the presence of likely storage materials for over a year under typical in-use pressures and temperatures. The stability of HFC-125, HFC-227ea, and FC-218 was excellent. Samples of CF_3I were observed to be stable at 23 °C; however, during exposure at 100 °C and especially at 150 °C, small amounts of CO_2 and an unknown chemical appeared whose concentration increased with exposure time. Each of the four chemicals is compatible with a choice of materials for the storage containers: gasket materials, lubricants, and metals. Each agent caused only minor swelling in at least three of the elastomers and at most moderate swelling in the greases. The long-term deformation of the seven elastomers showed that at least two elastomers are compatible with each of the agents. The long-term stability of the seven elastomers, evaluated using compression set measurements, showed that at least two elastomers were not subject to excessive permanent deformation in each of the four agents. Long-term immersion of coupons of container metals at storage temperatures and pressure in each of the four candidate agents or halon 1301 produced little mass change or visual corrosion, although CF_3I showed some small interaction with three of the metals at high temperature. Slow strain rate tests of the metals in four of the agents at 20 °C and 150 °C and 5.86 MPa showed no difference from metal samples immersed in inert argon. CF_3I was not compatible with a titanium alloy at elevated temperature.

Safety Following Discharge. Predictions of the production of HF during fire suppression indicate that fires in dry bays are suppressed sufficiently quickly that only small amounts will be formed. For engine nacelle fires, the model developed here predicts that HFC-227ea, HFC-125 and FC-218 would produce similar amounts, while the more efficient CF_3I would produce far less. Exposure to surfaces heated by the fire would produce more HF from CF_3I than from an equal amount of the other three chemicals. Samples of aircraft materials that might be located near or downstream of an engine nacelle fire were immersed in 1 % or 10 % aqueous HF and then stored at 100 % relative humidity for 30 days at 22 °C. No significant degradation was seen. While accidentally-discharged CF_3I will decompose under both normal outdoor and indoor lighting, laboratory measurements and dispersion modeling show that the concentrations of potentially toxic photolysis products (HF, COF_2) are not likely to be sufficient to hinder prompt escape.

Discharge Performance. All four of the chemicals can be expected to discharge and disperse well from their storage and distribution systems at temperatures near 20 °C. At the lower temperatures experienced during high altitude flight or cold weather operation, CF_3I and HFC-227ea, with their higher boiling points, would not disperse as well as the other two chemicals.

Optimal Currently Available Option. Based on the results available in October, 1994, we recommended the selection of HFC-125 as the optimal candidate for Phase III examination for both engine nacelle and dry bay fire suppression. FC-218 possesses an extremely long environmental lifetime. While CF_3I was the most efficient suppressant, being virtually a drop-in replacement for halon 1301 in some tests, it had three drawbacks: its inhalation toxicity in cardiac sensitization testing, inconclusive stability and materials compatibility data, and a relatively high boiling point. HFC-227ea has a similar boiling point, and thus would also perform less well at low temperatures. The knowledge that has accrued in the final year of the project has not changed our perspective on this recommendation. During the fall 1994 meetings of the Technology Transition Team, these data and the results of an extensive and carefully constructed series of real-scale live-fire tests at Wright Patterson Air Force Base led the Team to recommend HFC-125 as the candidate for Phase III evaluation for both applications.

Part 2: Knowledge to assist in the development of engineering design criteria and suppressant system certification

Agent Discharge Behavior. The rate at which a suppressant will emerge from its storage container depends on the thermodynamic properties of the stored fluid and any pressurizing gas as well as the initial conditions in the container. Effective design of the suppression hardware requires quantitative performance measures for these chemicals. The NIST computer code PROFISSY accurately calculates binary vapor-liquid equilibria within the storage bottle, data needed by storage system designers. Laboratory data show that the nitrogen dissolved in the stored liquid agent significantly affects the agent discharge whether in a direct release system for dry bays or a piping system for engine nacelles. A NIST-developed storage bottle discharge model, which incorporates nitrogen degassing, generally predicts agent discharge times to within a factor of two, but occasionally a factor of four. The only required inputs for the model are the initial conditions in the vessel. For plumbed engine nacelle systems, a new, validated model can be used to facilitate calculations of transient, two-phase pipe flow. We have developed a flow chart to organize the use of these tools into a coherent process for optimal design of a new discharge system.

Engine Nacelle Fire Suppression Guidance. The selection of the mass of agent to be stored on an aircraft should be based on the amount needed to quench the worst realistic fire. For engine nacelles with ribs and other obstructions, this is a baffle-stabilized pool fire. Heating the air stream and, to a lesser extent, increasing the pressure, increases the mass of agent needed for flame extinction, while the fuel flow had no significant effect. A step-by-step procedure has been developed that gives guidance in determining fire suppressant concentrations and discharge times for flame extinguishment. It shows the relative importance of agent injection duration, air flow and velocity, agent/air mixing mode, and fire scenario. A reasonable target concentration for an agent in the fire zone is that needed to quench the most flammable fuel/air mixture, both ensuring flame suppression and preventing re-ignition during the period of injection.

Real-Time Concentration Measurement. Determination of the dispersion of the suppressant following discharge requires measurements of its concentration that are well-resolved in both time and space. We examined two instruments (based on thermal conductivity and infrared absorption) in order to assess their ability to perform *in situ* measurements with the ~1 ms time resolution needed for dry bay applications. Neither performed well. Both were improved extensively and showed potential. However, both need further work to be useful in practical systems. A review of the sensing literature shows a number of alternative approaches, but none that could be accurately adapted to this application without a significant development and testing effort. The most promising are time-resolved mass spectrometry and mid- and near-infrared absorption combined with fiber optics to provide easy access and the needed spatial resolution.

Certification Guidance. HFC-125 closely replicates the physical and dispersion properties of halon 1301. Thus it is an excellent simulant for hardware development and can be used to certify those engine nacelle fire suppression systems that still rely on halon 1301. The mixing time for agent entrainment behind an obstacle is different under non-fire conditions than for fire conditions. A method for using the non-fire data to approximate the fire suppression concentration has been developed.

Interaction with Metal Fires. In laboratory experiments, none of the four alternative chemicals nor halon 1301 showed exacerbation of burning of magnesium or titanium rods. It is not explicitly known why the flare-ups observed during the introduction of halon 1301 to real metal fires were not observed here. However, it may be useful to know that in the circumstances replicated in the laboratory tests, the alternative agents did not worsen the combustion relative to that with halon 1301 present.